

Statistical Characteristics of Suction Pressure Signals for a Centrifugal Pump under Cavitating Conditions

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Centrifugal pumps are often used in operating conditions where they can be susceptible to premature failure. The cavitation phenomenon is a common fault in centrifugal pumps and is associated with undesired effects. Among the numerous cavitation detection methods, the measurement of suction pressure fluctuation is one of the most used methods to detect or diagnose the degree of cavitation in a centrifugal pump. In this paper, a closed loop was established to investigate the pump cavitation phenomenon, the statistical parameters for PDF (Probability Density Function), Variance and RMS (Root Mean Square) were used to analyze the relationship between the cavitation performance and the suction pressure signals during the development of cavitation. It is found that the statistical parameters used in this research are able to capture critical cavitation condition and cavitation breakdown condition, whereas difficult for the detection of incipient cavitation in the pump. At part-load conditions, the pressure fluctuations at the impeller inlet show more complexity than the best efficiency point (BEP). Amplitude of PDF values of suction pressure increased steeply when the flow rate dropped to 40 m³/h (the design flow rate was 60 m³/h). One possible reason is that the flow structure in the impeller channel promotes an increase of the cavitation intensity when the flow rate is reduced to a certain degree. This shows that it is necessary to find the relationship between the cavitation instabilities and flow instabilities when centrifugal pumps operate under part-load flow rates.

Keywords: Centrifugal pump, Cavitation, Suction Pressure, Statistical Characteristic, Partial flow rates

Introduction

Cavitation is a common fault in centrifugal pumps and, if a pump operates under cavitating conditions, the following situations will always be observed: pump capacity reduced, head degradation, and high levels of noise and vibration. The erosive damage of the exposed surface is also responsible for cavities. Although the implosion of

the cavities is generally associated with undesired effects [1], it provides a powerful method for the monitoring and diagnosis of cavitation in the centrifugal pump, such as the detection of cavitation in centrifugal pump by vibration methods [2]. For reliable cavitation detection, an appropriate detection technique should be used. There are many ways to detect cavitation, including vibration signal measurement mentioned above, the pressure fluctua-

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Nomenclature

H	pump head (m)	RMS	root mean square
n	rotating speed (r/min)	u	velocity (m/s)
n_s	specific rotating speed	Greek letters	
$NPSHA$	net positive suction head available (m)	η	pump efficiency (%)
$NPSH_b$	net positive suction head breakdown (m)	μ	mean value
$NPSH_c$	net positive suction head critical (m)	ρ	density (kg/m^3)
$NPSH_i$	net positive suction head inception (m)	σ	standard deviation
$NPSHR$	net positive suction head required (m)	σ^2	variance
p	pressure (Pa)	Subscripts	
PDF	probability density function	0.5%, 1%, 2%, 3%, 4%	percent of head drop
Q	volume flow rate (m^3/h)	BEP	best efficiency point

tion signal using pressure transducers [3], the waterborne acoustic signal from hydrophones [4], and the visual observation of cavitation criterion by high-speed digital cameras [5]. Angular speed of the pump shaft and stator current of the motor driving the pump were also proposed by Alhasmi to detect the fluctuations of the hydraulic load on the motor [6].

For pump designers, it is important to know the beginning, developing and breakdown of cavitation in the pump. Besides, it is a must to ensure that the net positive suction head available ($NPSHA$) is greater than the net positive suction head required ($NPSHR$) during the operation of the pump. When the suction pressure is gradually reduced, three critical $NPSH$ values should be identified in the cavitation performance graph, the first critical value is $NPSH_i$ at which cavitation first appears. As the pressure further reduces, the degradation of pump performance will occur, while the $NPSH_c$ is defined at which the head drops to a certain value. In the present work, the $NPSH_c$ value shows the condition that the pump head begins to drop. Further reduction in the suction pressure will lead to head breakdown, denoted by $NPSH_b$ [7,8]. It was found that the cavitation instabilities start to occur in the range where the head is not yet decreased, whereas the dynamic loads on the shaft and the blades increase steeply in pumps. Therefore, it is significant to further study the cavitation characteristics to ensure the reliability of the pump operation.

In the current research, concerning the development of cavitation in a centrifugal pump, experimental investigations have been carried out in a closed hydraulic test rig. The relationship between the cavitation performance and the suction pressure signals were carried out to detect and diagnose the cavitation pattern in a centrifugal pump. Both the average pressure and pressure pulsation at the impeller inlet have been adopted during the process of cavitation development. The statistical parameters for PDF, Variance and RMS were used to analyze whether they could be used to detect the degree of pump cavita-

tion. The cavitation performance under part-load flow rates was also analyzed in the paper.

Experimental Setup and Description

Experimental apparatus

The test equipment is shown in Fig. 1, which is a closed hydraulic test rig and consists of three parts: the recycle water-flow loop, the model pump, and the data acquisition equipment. The facility water is held in 4.5m^3 stainless steel reservoir tank, a rotary-vane vacuum pump is used to adjust the pressure inside the reservoir tank, and the flow rate is varied by the outlet butterfly valve and is measured by a turbine flowmeter. A 7.5 kW AC electromotor powered by a variable frequency controller was used to drive the test pump. The rotational speed is measured using a photoelectric tachometer. Both the suction and discharge pressure signals are measured by piezoelectric pressure transducers, including two dynamic pressure transducers (HM90) and two static pressure transducers (CYG1102). In order to ensure the stability of the average pressure, four-point connections is adopted; the positions of the sensors are shown in Fig. 2. All the signals were identified and stored in the computers for further analysis.

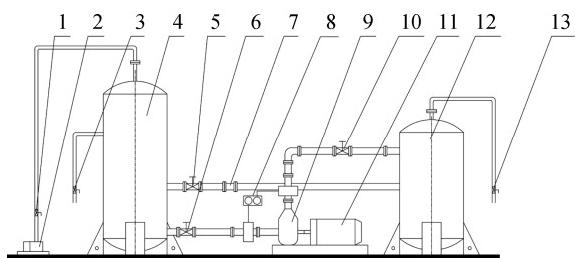


Fig. 1 Schematic of the closed test rig (not to scale). 1, 3, 13) Ball valve; 2) Vacuum pump; 4) Pressure tank; 5, 10) Butterfly valve; 6) Gate valve; 7) Turbine flowmeter; 8) Static pressure transmitter; 9) test pump; 11) electromotor; 12) buffer tank.

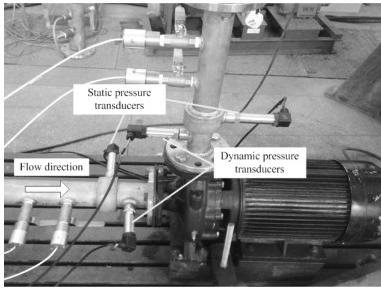


Fig. 2 Position of the pressure sensors.

General Overview of the Pump Performances

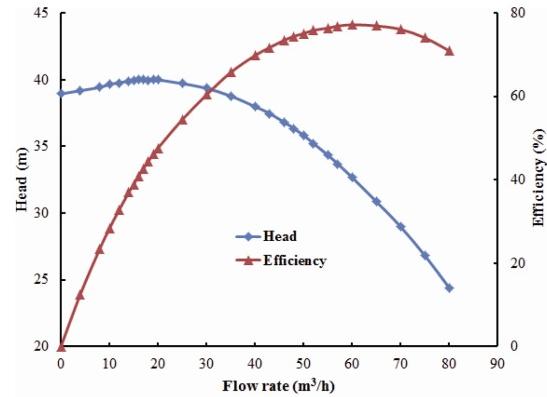
The test pump used in this paper was a single-stage and single-entry centrifugal pump made up of a six-blade impeller and a volute with a specific speed of $n_s=101.6$ at the best efficiency point ($n_s = 3.65nQ^{0.5}H^{0.75}/60$). The design parameters of the pump are the head $H_{BEP}=32$ m, the rotating speed $n=2900$ r/min, and the flow rate $Q_{BEP}=60$ m³/h.

Fig. 3 shows the experimental performances of the test pump, including the overall performance in noncavitating condition and the cavitation tests. For the experimental cavitation procedure, the inlet pressure drop is realized by the vacuum pump, while the rotating speed and the flow rate are fixed to constant values. The cavitation tests were carried out among the range of flow rate from 13 m³/h to 65 m³/h. It is noted at the design flow rate that the value of $NPSHR$ is 3.1 m (the $NPSHR$ corresponding to a 3% drop in the pump head). As the hump characteristic of head-flow curves, it can be seen that the cavitation performance curves are almost coincident at three deep part load conditions. Five $NPSH$ curves for percentage head drops (i.e., 0.5%, 1%, 2%, 3% and 4%) at various flow rates and were also plotted in Fig. 3 (b).

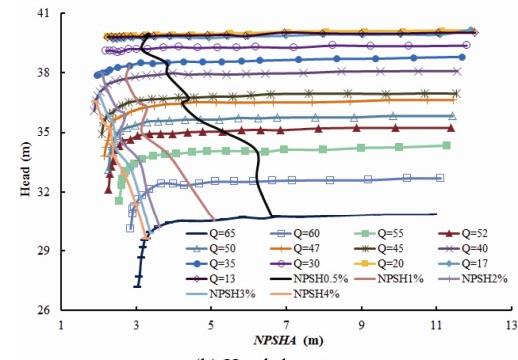
As mentioned above, three critical $NPSH$ values should be identified to describe the development of cavitation. Take the cavitation performance of 60 m³/h as an example. As the cavitation pattern cannot be directly observed in our experiment, and the head remains constant until the suction pressure drops to a certain value, the exact $NPSH_i$ value is, therefore, impossible to be identified in Fig. 3 (b). The condition that the pump head begins to drop ($NPSH_c$) is also difficult to establish, as the tendency of head drop is slow in the range of the $NPSHA$ value between 6.12 m ($NPSH_{0.5\%}$) and 4.69 m ($NPSH_{1\%}$). The head breakdown is established at the $NPSHA$ of 3.36 m, which almost coincides with the value of $NPSHR$.

Several different $NPSHA$ conditions at Q_{BEP} were selected to analyze the characteristics of the impeller suction pressure pulsation, as shown in Fig. 4. The vertical axis shows the amplitude of impeller suction pressure pulsation coefficient, which is defined as

$$c_p = \frac{2(p - \bar{p})}{\rho u_1^2} \quad (1)$$



(a) The overall performances in noncavitating regime



(b) Head-drop curves

Fig. 3 Experimental performances of the test pump.

where p and \bar{p} are the static and time average static pressures, respectively, and u_1 is the circumferential velocity at the impeller inlet.

As can be seen from the figures, characteristics of suction pressure change dramatically with the development of cavitation conditions. In cavitation-free condition, there is an obvious periodic trend of the suction pressure pulsation, and the type is mainly caused by rotor-stator interaction. At the initial stage of cavitation ($NPSHA=7.15$ m), no obvious change for pressure fluctuations compare with the ones at $NPSHA=11.1$ m, except the amplitude of the pressure fluctuation increased. A further decreasing of the suction pressure pulsation will lead to the range of pulse amplitude decrease and will also disturb the normal frequency. One possible reason is that the generation and collapse of vapor bubbles gradually play a dominant role to the pressure fluctuations with the deterioration of cavitation. Therefore, suction pressure pulsation could be used as a cavitation characteristic signal to detect the development of cavitation.

Statistical Methods and Definitions

In the present study, the statistical parameters for PDF, Variance and RMS were used to analyze the relationship between the cavitation performance and the suction pressure signals during the development of cavitation.

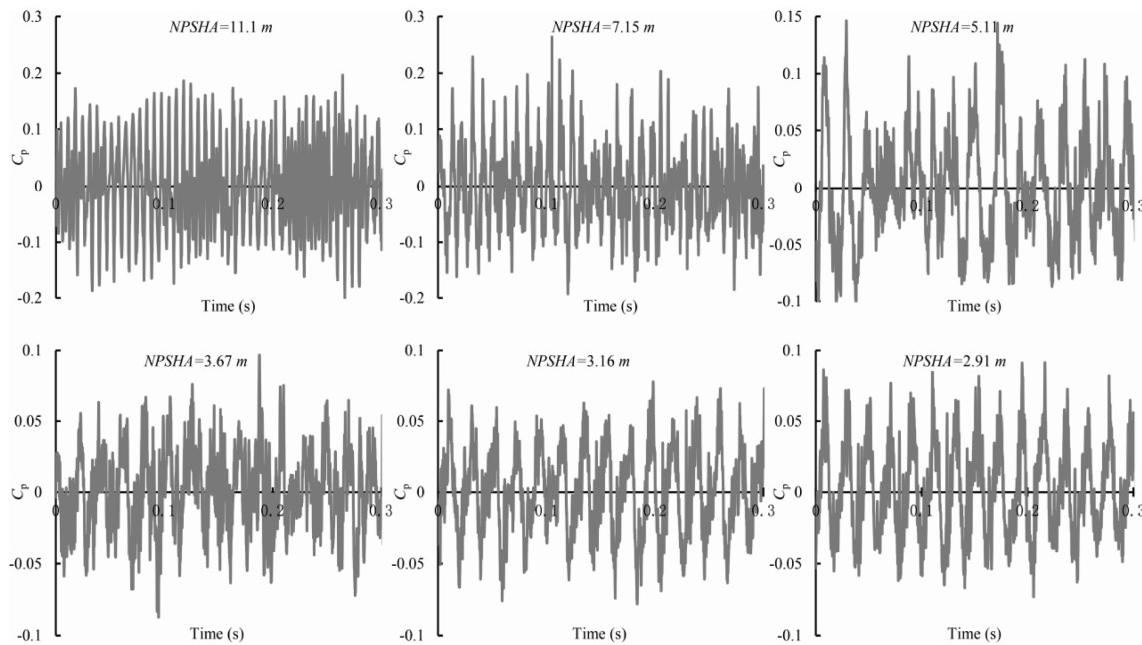


Fig. 4 Time domain signals of impeller suction pressure pulsation at Q_d .

The PDF is a function that describes the relative likelihood for this random variable to take on a given value. This method has been adopted by Faisal to monitor the cavitation performance in a centrifugal pump [9]. In his research, the shape of the PDF curve is altered with the flow rate increasing, while the changing PDF values with the decreasing pressure were not obtained. The PDF value of a quantity x is defined as

$$\text{PDF} = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}}. \quad (2)$$

Where μ is the mean value of the quantity x and σ^2 is the variance, which is defined as

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^N (x_i - \mu)^2. \quad (3)$$

The RMS value is often used to describe the square root of the average of squares of a set of numbers, which is defined as

$$p_{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^N p^2(i)}. \quad (4)$$

Where N is the total number of samples.

Results and Analysis

Statistical characteristics analysis of suction pressure fluctuations

Fig. 5 shows the probability densities of suction pressure fluctuations at Q_{BEP} . With the continuing decrease in suction pressure, pump cavitation inevitably happens, and the shape of the PDF curves also change. The peak and the width of the curve are about 0.075 and 26, re-

spectively, in cavitation-free condition. The tendency of the PDF curve is to broaden in span at the early stage and then narrow as the suction pressure further decreases. The width of the PDF curves would keep almost constant when the $NPSHA$ drops to below 4.69 m, and the value of the span is about ± 4.8 . This behavior may be the reason that 3σ criteria can be used for cavitation monitoring in the centrifugal pump [10]. It is important to note that the criteria value is not a constant number, but will change with the flow rates. Fig. 6 presents the probability densities of suction pressure at $65 \text{ m}^3/\text{h}$. The tendency of the PDF curves was similar to the one at $60 \text{ m}^3/\text{h}$, except for the width of the PDF curves, as the value is about ± 3.6 .

In order to clarify the influence of cavitation on PDF of suction pressure signals, amplitude of PDF curve against $NPSHA$ are presented in Fig. 7. Two interesting aspects could be summarised from the figure. Firstly, the tendency of the peak value was described. A slight change of the peak value was obtained at the early stage of suction pressure drop, and a steep increase in the value occurred at full developed cavitation condition. The results indicated that the method of PDF analysis is suitable for evaluating the cavitation performance of centrifugal pumps.

Secondly, it was found that the peak value is able to capture the critical cavitation condition that head begins to drop and cavitation breakdown condition occurs. It is difficult for the detection of incipient cavitation in the pump. The reason may be that vapour bubbles occurred in the impeller channel are not enough to break the continuity of the liquid at the early stage of cavitation. Hence vapour bubbles have less impact on the overall perform-

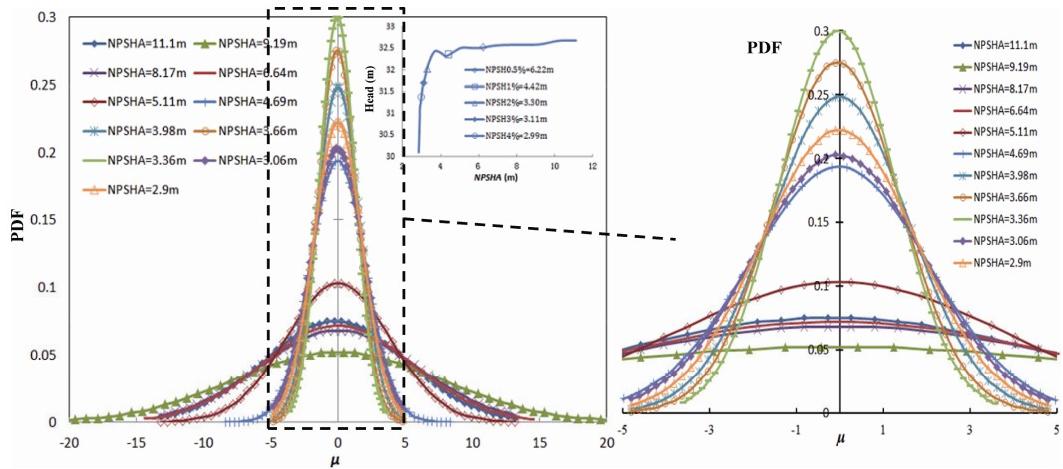


Fig. 5 Probability densities of suction pressure fluctuations for design condition.

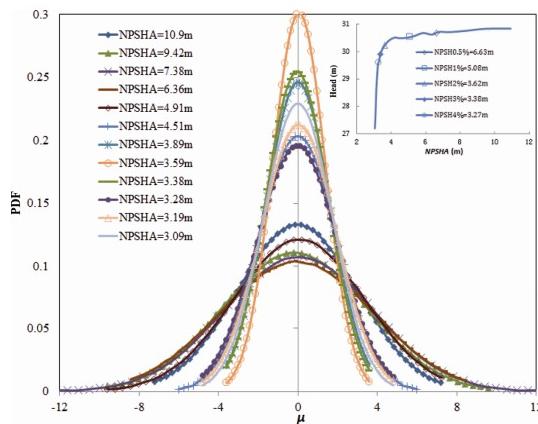


Fig. 6 Probability densities of suction pressure fluctuations at $65\text{m}^3/\text{h}$.

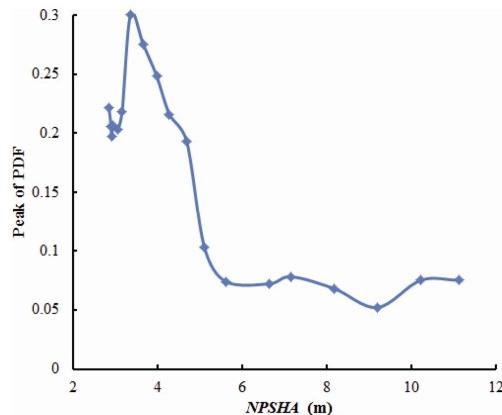


Fig. 7 Amplitude of PDF curve against $NPSHA$

ance or pressure fluctuation of the pump. While a definite change occurred in the peak and span of PDF when the value of $NPSHA$ is lower than 5.11 m, the $NPSHA$ dropped from 5.11 m to 4.69 m and led to an increase of the peak value from 0.103 to 0.193. As observable head

drop is occurred in these cavitation stages, $NPSHA=5.11$ m can be used to establish the critical cavitation condition when the pump head begins to drop. When $NPSHA=3.36$ m, which corresponds to cavitation breakdown condition, the maximum peak value was also obtained.

It can be seen from Fig. 8 that the trend followed by the Variance and RMS values of suction pressure signal is very similar. There are maximum values of the two curves at the $NPSHA$ of about 9.19 m, but the reason of the presence of this phenomenon was not clear. This is partly because the flow pattern cannot be discernible to the eye in our experiment. The other is that the phenomenon was not found in off-design conditions. Compared with the amplitude of PDF curve, a sharp decrease in the rate of change of slope of the Variance and RMS curves between 5.61 m and 4.69 m shows the critical cavitation condition that pump head begins to drop. In addition, the minimum value of RMS curve as well as Variance curve appears at $NPSHA=3.36$ m, which coincides with the maximum peak value of the PDF curve. A limited conclusion may be given that the statistical parameters used in the paper were good markers for established cavitation and cavitation breakdown condition, but not its onset.

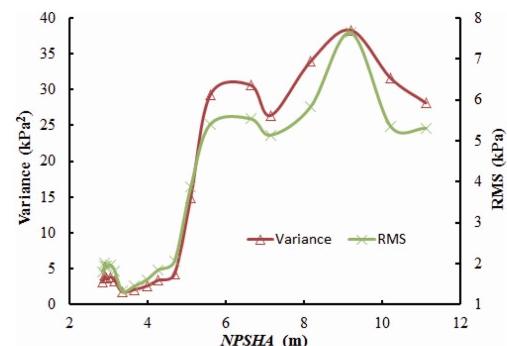


Fig. 8 Variance and RMS curves of suction pressure signal

Relation between flow rates and cavitation performances

As mentioned above, large scale cavitating structures occurred near the impeller inlet are the main reason for the dramatic change of the three statistical parameters at normal flow rate. However, attention also should be paid to the cavitation performance at off-design conditions. In those conditions, the interaction between unsteady cavitation and separated flow makes the flow structure in the pump complicated. It is mentioned that flow separation phenomenon would occur at the blade leading edge when the pump operating at the off-design conditions. The phenomenon does not directly produce cavitation, but may boost the unsteady cavitation. Fig. 9 shows the amplitude of PDF curves at different suction static pressure; the static pressure value is represented by the gauge pressure and marked in the figure. During the process of experiment, keep the suction static pressure at an exact value, and then the curves can be obtained by adjusting the flow rate of the pump. The selected curves show the flow transition, with decreasing flow rate, from a flow rate of $65 \text{ m}^3/\text{h}$ to conditions of large scale flow separation in the impeller passage.

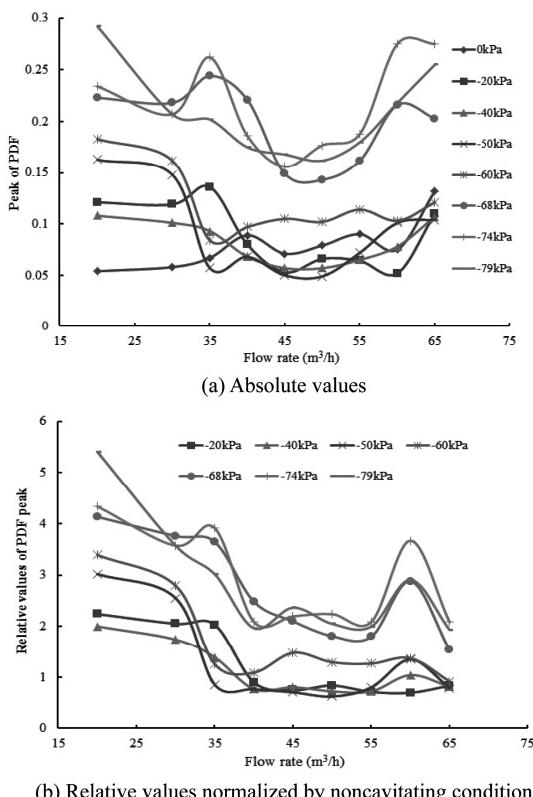


Fig. 9 Amplitude of PDF curves of suction pressure signal for different flow rates.

It was found that the trend of the peak value is almost decreasing with the decrease of the flow rate at the suction pressure of 0 kPa. As no cavitation occurred in the

pump, the condition can be considered as a reference. With the flow rate decreased, a clear change of the peak of PDF can be found in Fig. 9(a). For the flow rates greater than $60 \text{ m}^3/\text{h}$, the peak value rises rapidly; for the flow rates between $55 \text{ m}^3/\text{h}$ and $40 \text{ m}^3/\text{h}$, there is a nearly constant peak of PDF level. At less than $40 \text{ m}^3/\text{h}$, the peak value has begun to increase.

In order to describe the relation between the flow rates and cavitation performances more clearly, the relative value normalized by the peak value of noncavitating condition was obtained, as shown in Fig. 9(b). It was found that the relative value undergoes a clear change with the decrease of the flow rate and suction pressure. For the suction pressure lower than -60 kPa , the peak value rises rapidly, indicating that cavitation has been established. A clear increase in peak value at about $40 \text{ m}^3/\text{h}$ shows that large scale flow separation in the impeller channel has a negative effect on unsteady cavitation.

A possible explanation of cavitation phenomenon in a centrifugal pump at partial flow rate is as follows: with the pressure decreasing at the pump inlet by increasing the volumetric fraction of vapor, cavitation will gradually fill the impeller channel and disturb the normal flow pattern near the entrance of the impeller blades. At the flow rates between $55 \text{ m}^3/\text{h}$ and $40 \text{ m}^3/\text{h}$, an increasing incidence angle destabilizes the vortex. As a result, cavitation has little effect on the running state of the pump. At less than $40 \text{ m}^3/\text{h}$, unstable large-scale vortexes appeared in the impeller channel. Cavitation may promote the shedding of the vortexes, which leads to a dramatic increase of PDF amplitude with the decrease of flow rate.

Conclusions

An experimental investigation has been carried out to research the pressure fluctuation at the impeller inlet during the development of cavitation. Three different statistical parameters were used in the paper for the detection of the onset of cavitation. The results indicate that:

1. The three statistical parameters of pump inlet pressure pulsation can be used as definite indications of critical cavitation condition. The pump head begins to drop and cavitation breakdown condition occurs, yet it is difficult to detect incipient cavitation in the pump.

2. As the suction pressure drops to a certain value, the rapid increase in PDF peak values can be found at all selected flow rates. The span of PDF curves keep almost constant, but will change with the flow rates. The steep increase in peak value could be used to establish cavitation, which is superior to the method determined by a 3% pump head drop.

3. Cavitation inside the impeller has an obvious influence on the flow pattern when the flow rate drops to a

certain value, as well as a dramatic increase of PDF amplitude.

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